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Report on the Workshop on Multiangular Remote Sensing for Environmental Applications

Jeffrey L. Privette
Donald W. Deering
Goddard Space Flight Center
Greenbelt, Maryland

Diane E. Wickland
NASA Headquarters
Washington, D.C.

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland
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Jeffrey L. Privette and Donald W. Deering

Biospheric Sciences Branch, NASA's Goddard Space Flight Center, Greenbelt, MD

Diane E. Wickland

Terrestrial Ecology Program, NASA Headquarters, Washington, DC

Abstract

The NASA Terrestrial Ecology Program sponsored a workshop on January 29-31, 1997, at the University of Maryland Conference Center, to review the progress and the future directions of multiangular reflectance research. More than 65 investigators, representing 10 countries, participated in the presentations, poster session and discussions associated with this workshop. Held at the dawn of the EOS era, this workshop was intended to determine the progress made in bidirectional reflectance distribution function (BRDF) research, the key areas needing new research emphasis, and the mature aspects of BRDF research that can be exploited immediately to support ecological research. Presentations on the first day were primarily dedicated to reviewing the context of BRDF research in NASA's Global Change Research Program and the development of physically-based models and algorithms. Afternoon discussions focused on the lessons learned in key areas of BRDF remote sensing, from atmospheric correction to retrieval of canopy structural information. On the second day, presentations were given on recent applications of computationally efficient "simple" BRDF models. Discussions in the afternoon focused on moving BRDF research into a more applied stage, particularly in concert with EOS data sets, and assessing its role with respect to other data sources (e.g., hyperspectral). The morning of the third day was devoted to setting priorities for recommendations. This report summarizes the progress made at the workshop, with particular emphasis on the outstanding research problems remaining and the recommendations for improved ecological application. Four appendices follow the main report, including I) List of Acronyms, II) Reports from the Break-out Discussions, III) Workshop Agenda, and IV) List of Participants.

Foreword

The 1997 Workshop on Multiangular Remote Sensing for Environmental Applications was convened primarily because I felt it was time to assess progress over the past 15 years on research into the vegetation bidirectional reflectance distribution function (BRDF) and related directional reflectance phenomena. With the advent of NASA's Earth Observing System (EOS) and other satellites with multidirectional viewing capability, it also seemed time to assess future research directions. The workshop was highly successful in addressing both topics, and has provided me with many useful insights that should prove helpful in steering the BRDF element of the Terrestrial Ecology Program into the future.

Overall, I found the workshop more successful in assessing the accomplishments of past research than in identifying, and assigning priority to, focused directions for future BRDF research. I left the workshop very satisfied that NASA's past investment was well spent and rather proud of the contributions this fundamental science had made to the next generation of algorithms for correcting remotely sensed data and generating improved data products. I heard several really big messages at the workshop, which I hope most participants agree are fair assessments of what was said, and I also carried away a number of impressions that, I suspect, are unique to my own experiences at the workshop.

Major Messages

Here are the big messages I heard that summarize accomplishments and point toward research needs:

- Research in the past 15 years has conclusively established that the Earth's surface is non-Lambertian, and any future analyses, excepting perhaps the most simple and crude of approximations, cannot legitimately assume Lambertian properties. Reflectance anisotropy is significant.

• The current generation of advanced satellite data correction algorithms and data product algorithms use BRDF understanding produced in part by the NASA remote sensing science program element. This understanding is even more extensively and pervasively exploited in EOS algorithms. There are nice demonstrations already of how classification accuracy, vegetation indices, and Fraction of APAR (fAPAR) retrievals can be improved using multiview angle data. (But note, at least with respect to the improved vegetation indices, that the improvement follows because of sensor characteristics, not necessarily because of any inherent problems with the vegetation index itself.)

• One of the unique capabilities of multidirectional remote sensing is in the correct derivation of the Earth's albedo. EOS albedo data products will be dramatically improved over past albedo data products because of their use of directional data. (However, EOS sensors still do not sample the full hemisphere as well as could be done.)

• We have a sophisticated understanding of how directional radiation interacts with vegetation canopies but, to date, have been unable to use it to derive useful ecological information about vegetation canopies. There is a disconnect between the structural parameters determined by BRDF studies and the structural parameters governing ecosystem patterns and processes. This disconnect is at least partially responsible for the limited use of BRDF understanding by ecologists. There may be a need for ecologists to specify the structural properties of ecosystems that they could use significantly, and for remote sensing specialists to focus on alternative characterizations of vegetation structure.

• There is an urgent need to gain experience from real satellite data, exercising and learning from Polarization and Directionality of Earth's Reflectances (POLDER), Multiangle Imaging Spectroradiometer (MISR), and Moderate Resolution Imaging Spectroradiometer (MODIS), before moving ahead on improvements to existing approaches.

Other messages of interest, but of a more detailed and/or less fundamental nature, are as follows:

• No one model can handle BRDF for all cover types; approaches to the problem must either first stratify by land cover or use parametric models, such as kernel-driven. (Thus, land cover becomes an important data product to pursue for stratification purposes in support of BRDF research.)

• BRDF analyses are inherently quantitative; thus, there is a need for good calibration and radiometric and geometric corrections to do good BRDF work.

• There are only a few data products that are truly unique to multiview angle data. These include albedo and atmospheric phase function. Many other data products can also be derived from other types of remotely sensed data—although BRDF information may be able to improve the derivations.

New Impressions

Perspectives I gained, but which were not much discussed at the workshop:

• The recent development of new, simple approaches to modeling directional effects appears to have been driven by the pressures to generate practical, implementable algorithms for correcting specific satellite sensors and their data products. These simplified approaches would not have been possible without the understanding that has been derived from the more complex, theoretically rigorous models that preceded them.

• It is possible that more innovative thinking may be needed concerning ways to utilize multi-directional data. More intimate interactions between ecologists and BRDF specialists that can break down traditional lines of thought and approaches to using and/or characterizing remotely sensed data may be in order—as may be approaches not limited to one part of the spectrum or one type of remotely sensed data.

• Validation activities for post-launch evaluation of new sensors requires more attention. If comprehensive, clean, in situ data sets are necessary and are to be obtained, the BRDF community may need to take responsibility for producing them.

Future Directions

When I reviewed the draft workshop summary that Jeff Privette and Don Deering prepared, including the break-out group reports, I had great difficulty extracting a short list of high-priority, well-justified recommendations for future research directions. There were a number of recommendations, some very specific and detailed and others very broad and comprehensive, but none that really hit me over the head as an obvious next step with promise for major scientific and practical returns. I agree with the recommendations encompassed in the body of this report, and will weave them into future research priorities for the Terrestrial Ecology Program, but I think that now is not the time to chart major new directions. When all is said and done, I think that the strong message I heard at the workshop with regard to there being an urgent need to gain experience from real satellite data, exercising and learning from POLDER, MISR, and MODIS explains this situation very well. Thus, I intend to make certain that the program is well positioned to exploit these new sensors in the next few years and plan to pick up the question of new directions and most promising applications a few years post-launch of EOS.

In the meantime, I intend to follow the recommendations in this report, encouraging research proposals that explore data fusion approaches, consider scaling questions, introduce innovation and team work to bridge the gap between ecological vegetation structure requirements and BRDF vegetation structure requirements, and offer significant advances in streamlining current approaches and/or providing better validation. Research that focuses on effective exploitation of current and near-future satellite data will be preferred.

Acknowledgments

The BRDF Workshop would not have been possible without the dedication, hard work, and scientific leadership of Drs. Don Deering and Jeff Privette of NASA Goddard Space Flight

Center. I am in their debt for the excellent leadership they provided. Don deserves special recognition for volunteering to organize the workshop when first confronted by my skepticism concerning the value/payoff of past NASA investments in BRDF research. Jeff deserves special recognition for taking the lead on developing the workshop agenda and preparing this workshop report. We are all grateful to Jorge Scientific Corporation for capably handling the logistics of the workshop.

Diane E. Wickland
Manager, Terrestrial Ecology Program
NASA Office of Mission to Planet Earth

Introduction

Twenty-five years ago, when NASA launched its first terrestrial imager (Landsat 1), the remote sensing community lacked an understanding of the mechanisms determining the measured radiances, particularly the directional characteristics which usually were assumed to be uniform. The data were therefore treated as either pictorial images subject to visual interpretation or as statistical distributions of spectral signatures that could be used to automatically recognize thematic categories of land cover. Limitations in our ability to understand signatures over space and time and to characterize more fully terrestrial processes by pattern recognition revealed that better comprehension of the radiation processes governing remote observations was necessary.

In response, NASA began funding research into the vegetation bidirectional reflectance distribution function (BRDF) and related directional reflectance phenomena—often collectively referred to as BRDF. The BRDF is an intrinsic surface radiation characteristic that affects all terrestrial remote sensing measurements. This research involved much basic, theoretical work, including modeling. Research to further develop and test the models generated requirements for multiangle measurements that were met through the development of laboratory, field and aircraft instruments. The resulting measurements produced a diverse set of empirical data that helped validate the theoretical findings and expose characteristic reflectance phenomena that varied with land cover type and condition.

Program advances naturally prompted attempts to move from the earlier qualitative remote sensing techniques into quantitative retrievals of Earth surface information. Two general methods to do this evolved in parallel. First, relatively simple, sometimes empirically-based, corrections for existing remote sensing techniques were formulated. These corrections included compositing algorithms and BRDF characterizations to reduce directional effects in the well-used vegetation indices, e.g., the Normalized Difference Vegetation Index (NDVI), which have been correlated with many vegetation and environmental variables. Second, the reliance of the surface BRDF on canopy properties led to inversions of physically-based BRDF models. In a typical inversion, a model's parameters are adjusted until the model reflectance estimates closely match a set of measured data. At this point, the model parameters are estimates of the surface properties.

Ramifications of the new quantitative methods have been substantial. For instance, simple BRDF corrections, provided by compositing and empirical relationships, led to the first global maps of biophysical parameters from National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data (e.g., Fourier wave Adjustment, Solar zenith angle adjustment, Interpolation and Reconstruction (FASIR) by Sellers et al., 1994). These have been used extensively in biosphere-atmosphere flux transfer (e.g., Sellers et al., 1996). Other composited AVHRR data sets are used to derive land cover classification schemes (e.g., DeFries and Townshend, 1994). More generally, increasing confidence in quantitative remote sensing algorithms has led directly to the design and ongoing implementation of more effective spaceborne remote sensing systems, especially the sensors, algorithms, and products under development for the Earth Observing System (EOS; Asrar and Greenstone, 1995) and the French POLDER sensor on Advanced Earth Observing System (ADEOS) I (Deschamps et al., 1994).

Nevertheless, to date most BRDF-derived products over large areas have found limited application in ecological research. In fact, only the simplest BRDF corrections have been applied over regional or global scales; the more sophisticated techniques have mostly been applied on a "point" scale. Moreover, consistently accurate algorithms to retrieve vegetation structure remain elusive. Contributing to the underutilization are a host of problems, including inadequate satellite data quantity and quality (e.g., insufficient angular sampling and calibration), computationally expensive algorithms, poor validation data sets and concerns about algorithm robustness and accuracy. However, during the EOS era, it is imperative that we be fully prepared to utilize the knowledge we have gained over the last decade. Specifically, we will soon have instruments (e.g., MISR, MODIS, POLDER) in space whose products strongly depend on our appropriate use of multiangle characteristics. These sensors will have unprecedented directional sampling and calibration abilities, and undoubtedly will present the best opportunity to develop and exploit multiangle technology to date. Accurate and effective use of EOS data are imperative to helping solve pressing questions on, e.g., global carbon balance. The issues that follow represent the BRDF research community's recommendations and suggestions for improving the quality and usage of terrestrial multidirectional remote sensing products.

Applicable BRDF Technologies

The workshop exposed many applications of BRDF research that have been, or are ready to be, used to generate operational products with satellite data. For example, a review of the EOS Morning pass EOS platform (AM-1) algorithm theoretical basis documents (ATBDs) (available at http://eospso.gsfc.nasa.gov/atbd/pg1.html) reveals that essentially all standard land products, and many atmospheric products, incorporate BRDF models in their generation. For MODIS, these include surface reflectance (atmospheric correction), vegetation index, albedo, BRDF characterization, leaf area index, net primary production, fraction of absorbed photosynthetically active radiation, and land cover classification. For MISR, essentially all products (e.g., surface bihemispherical albedo, aerosol optical depth, and aerosol phase function) intrinsically depend on a BRDF model since the coupled atmospheric and surface radiation equations are solved simultaneously. Some of these products (e.g., albedo, vegetation index) rely on highly parameterized "simple" BRDF models, while others (e.g., Leaf Area Index [LAI], fAPAR) rely on look-up tables generated by complex numerical BRDF models. In fact, some sensors (e.g., MISR) were developed specifically to take advantage of the angular signatures that, previous to the BRDF research, were relegated to data noise.

Although discussion of all AM-1 products and their BRDF dependencies is beyond the scope of this document, we highlight below two of the most mature applications of BRDF understanding. These include the estimations of geometrically normalized vegetation indices and spectral albedo.

Since the mid-1980s, global vegetation index maps based on NOAA AVHRR data have been produced by a number of groups (for a historical review, see Tucker, 1996). The vegetation indices have been correlated with many biophysical variables of interest to ecologists. Nevertheless, such maps remained seriously plagued by BRDF effects despite the use of rudimentary BRDF corrections. These corrections include nadir view angle normalization from Maximum Value Compositing (Holben, 1985), a process which selects the highest NDVI value from all observations of a target over a short time period. Recently, Sellers et al. (1996) produced more accurate global data sets in part by developing an empirical solar zenith angle correction. Li et al. (1996) began operationally using a kernel-driven BRDF model to correct both view and solar angle effects in AVHRR data over Canada. Kernel-driven BRDF models are linearized parameterizations of physically-based geometrical-optics and turbid medium BRDF models (Wanner et al., 1995). Upon launch of AM-1, 16-day and monthly maps of view angle corrected vegetation indices will be generated at 250 m, 1 km and 25 km spatial resolution. Post-launch, monthly maps of view and solar angle corrected vegetation indices at 0.25° x 0.25° spatial resolution will be generated from four MODIS spectral bands, which each have a spatial resolution of 250 or 500 m (Huete et al., 1996).

Albedo specifies the fraction of incident solar radiation that is reflected at Earth's surface and is a critical parameter for accurate climate and energy balance studies (Dickinson, 1983). Historically, albedo has been estimated from land cover maps in literature (e.g., Matthews, 1983). Although satellite data offer a tantalizing opportunity to create such maps, Kimes and Sellers (1985) showed that without BRDF correction, albedo errors greater than 40 percent can occur. Thus, Sellers et al. (1996) produced low resolution (1° x 1°) albedo maps using a 2-stream BRDF model whose parameters were in part determined by the BRDF-corrected vegetation indices mentioned above. Upon launch of the EOS AM-1 platform in 1998, however, global albedo maps will be produced every 16 days at 1 km x 1 km resolution (Strahler et al., 1995). These maps will be generated through the inversion of kernel-driven BRDF models. Due to superior instrument calibration, atmospheric correction, product validation and more numerous viewing geometries, these estimates should have unprecedented accuracy.

Outstanding Research Issues

The achievements above demonstrate an ability to correct BRDF effects in existing remote sensing data and products. However, the remote sensing community may realize only incremental future progress if it regards angular reflectance differences primarily as noise to be corrected rather than a signal to be exploited. Indeed, much work has shown that unraveling the angular signature through various methods (e.g., neural networks, BRDF model inversions) has the potential to reveal surface information not obtained by other remote sensing methods. For example, although inversions require more complex input data sets, their ability to simultaneously estimate multiple canopy parameters, as well as their proper treatment of radiation interactions at the surface, suggest they have great potential. Still, most efforts to exploit the angular signal have not matured to the point of delivering information of interest to the ecological community.

Workshop participants identified at least two major obstacles slowing this collaboration. First, the satellite data sets available have generally been of inadequate quality to exploit the BRDF signal. This has prevented large-scale (time and space) studies showing proof of advanced BRDF concepts. Because physically-based BRDF algorithms are inherently quantitative, their inversion requires well calibrated, atmospherically corrected data over a large range of sun-target-sensor geometries. Some satellites such as Landsat and Satellite pour L'Observation de la Terre (SPOT) are well calibrated but lack sufficiently diverse sampling geometries over short periods (required to assume a constant vegetation condition). Other sensors, such as AVHRR, may take samples over a range of geometries in a short time period, but are poorly calibrated and atmospherically corrected over most areas. Although in some cases (e.g., First ISLSCP Field Experiment [FIFE], Boreal Ecosystem Atmosphere Study [BOREAS]) a sufficient quantity of calibrated aircraft data exist (primarily from the Advanced Solid State Array Spectroradiometer [ASAS] multidirectional scanner), these data are difficult to georegister. Most workshop participants agreed that the AM-1 and POLDER data sets will permit the first serious opportunity to test multiangular models and algorithms at the appropriate scales. Nevertheless, current techniques and infrastructure are inadequate to collect large area ground data in a timely fashion in order to validate most vegetation structural products. The EOS Validation Program should significantly improve this condition.

A second, perhaps more serious issue is the marginal usefulness of past BRDF products in ecological research. In general, the canopy parameters used to describe the radiation regime are inconsistent with the parameters used to describe ecological processes. Still, three potential BRDF-related products were identified as critically important to the ecological community. These included satellite-derived maps of 1) land cover type, 2) vegetation structure and properties (e.g., LAI, crown size, ground cover fraction), and 3) fAPAR.

Probably the most significant of these is land cover type. Although relatively little published research exists on determining land cover from the BRDF shape, recent studies suggest that BRDF information can improve traditional land cover algorithms (Leroy et al., 1997). Not only is identification of land cover type important for ecological research, but it is required for inversions of physically-based BRDF models as currently configured. Research shows that the dominant structure contributing to coarse scale reflectance anisotropy can vary significantly. For instance, in areas of high relief, the slope and aspects of the terrain may produce the greatest influence, whereas over a flat forest the crown and gaps sizes may produce the greatest influence, and over flat grasslands the leaf area index and leaf angle distribution may contribute most. It is generally believed that sufficiently accurate models have been developed to handle each of these scattering cases if sufficiently accurate satellite data were available. Success has already been realized in retrieving structural variables in both forests (crown density and shape; e.g., Li and Strahler, 1985) and grasslands (LAI; e.g., Privette et al., 1996) from satellite data. However, the models used in these cases were geared toward specific land cover types (e.g., those that can be simulated by geometrical optics or turbid media). In reality, most moderate resolution pixels of Earth contain a mixture of land covers with different predominant structural scales (e.g., leaf and crown). Without a priori knowledge of the true land cover distribution, it is difficult to accurately determine the most important structural parameters and hence the proper model. Unfortunately, research shows that incorrect model use can produce significant errors in retrieved products (Running et al., 1996).

The above issues are presently limiting the use and effectiveness of advanced BRDF applications. However, even with land cover type and successful BRDF model inversion, the structural parameters used to characterize canopies in BRDF models, such as "effective LAI" and crown size, are not particularly relevant in ecological research. For example, a key structural quantity in many ecological models is the woody-to-herbaceous mass ratio. Presently, no physically-based BRDF models explicitly report this quantity, although it may perhaps be derived from some model parameters.

Research Recommendations

Given the successes and outstanding research problems noted above, five new research emphases are recommended below, together with several topics deemed in need of additional attention.

1. A recurring concern evolving from the workshop was the relative incompatibility between current remote sensing products, including those from BRDF inversion methods, and data fields needed for ecological process modeling. Workshop participants suggested that through *more frequent collaboration between remote sensing and ecological modeling scientists*, a convergence in parameterizations or data structures might be developed to foster wider use of remotely sensed data in ecological applications. Likewise, further *efforts to parameterize BRDF models with more ecologically relevant parameters* should also facilitate broader usage. Such parameterizations might, for example, involve new statistical characterizations of vegetation structure amenable to solving the radiative transfer problem in canopies. Likewise, *more end-to-end studies, where remote sensing products are used in ecological models whose outputs are appropriately validated*, should help identify the types, uncertainties, and spatial and temporal resolutions of the key parameters needed to link these communities more effectively.

2. *Improved in situ methods to indirectly characterize vegetation, both at the stand and landscape or regional level, are needed.* Although this information is required for land cover classification and remote sensing product validation, current methods of assessing canopy structure are relatively expensive, precluding application at sufficiently coarse scales (km). Development of new methods with *in situ* measurements could possibly be based upon previously collected data (e.g., FIFE, BOREAS) or designed around the acquisition of new ground data sets (e.g., Large-Scale Biosphere-Atmosphere Experiment in Amazonia [LBA]). The new methods must emphasize applicability to coarse scales such that accurate, quantitative validation data can be collected for global validation of BRDF and other remote sensing products.

3. *More efficient and reliable methods must be developed for inverting physically-based canopy reflectance models.* Although substantial effort has been invested in developing and understanding forward BRDF models, relatively few studies report efforts at improving the speed and accuracy of the inversion process. For example, most inversion algorithms use traditional "off-the-shelf" optimization routines with few, if any, improvements or modifications. Hence, computational efficiency is often cited as a detriment to the operational use of BRDF inversions. Look-up tables offer one clear possibility with which to improve speed, and are currently being

developed for use in both MODIS and MISR algorithms. Additional shortcut techniques should be developed.

4. *A new emphasis is needed on integrating data from other types of sensors* (hyperspectral, thermal, passive microwave, radar, Light Detection and Ranging Instrument [LIDAR]) *into BRDF applications and algorithms.* It is recognized that BRDF information presents a unique signal and should be exploited; however, the greatest potential may be realized when BRDF data are fused with other, highly uncorrelated data sources. For example, initial studies suggest a combined BRDF and spectral data approach can improve the accuracy of land cover classification. *Exploration of other applications and data types for data fusion are needed.*

5. *An improved understanding of reflectance scaling from leaf-to-canopy-to-landscape level is needed.* Although relatively simplistic 1-D turbid medium canopies appear well understood, a better understanding of scaling is needed for more realistic, finite-sized plants containing nonleaf material and gaps. This is particularly true for heterogeneous areas for which satellite-measured radiances can contain significant adjacency effects, or where topography is a factor.

Additional topics suggested for future research emphasis include the following:

- Atmospheric correction of satellite data, particularly improvements in the coupling of the surface BRDF with atmospheric radiative transfer schemes;
- Improved treatment of surface reflectance in climate models using current BRDF technology; and
- Understanding the effects of topography in Earth surface reflectance, and extending BRDF models to account for these effects.

Conclusions

The BRDF research community has made substantial progress in understanding the basic radiation and surface characteristics controlling surface reflectance. This progress has taken the form of advanced theory, sophisticated models, efficient operational satellite data corrections and compilation of various ground and aircraft data sets. Indeed, because sufficiently accurate and efficient BRDF models now exist, any future optical remote sensing algorithms can and should include operational BRDF correction when beneficial. Nevertheless, advanced BRDF methods have thus far not been used operationally, largely due to the inadequacy of current satellite data quality and quantity. Previous BRDF research helped lay the foundation for a new generation of satellite sensors such as ADEOS POLDER, launched in 1996, and the EOS AM-1 sensor suite, to be launched in 1998. With these instruments, sufficient high quality data should become available to exploit the BRDF signature more effectively, particularly when used in combination with other types of satellite data sets (e.g., radar, Light Detection and Ranging Instrument [LIDAR], thermal, microwave). Thus, the BRDF community must now focus on generating and validating new products of more direct utility to ecologists, such as maps of vegetation types and the fraction of photosynthetically active radiation absorbed by a canopy. Production of BRDF-derived products useful to the ecology research community will lead to a desire for more sophisticated products that can result from applying BRDF techniques to the extraction of useful vegetation structural attributes.

References

Asrar, G. and R. Greenstone (1995), 1995 MTPE EOS Reference Handbook, NASA Goddard Space Flight Center, http://eospso.gsfc.nasa.gov/eos_reference/TOC.html.

DeFries, R.S. and J.R.G. Townshend (1994), NDVI-derived land cover classification at global scales, *Int. J. Remote Sensing,* 15:3567-3586.

Deschamps, P.Y., F.M. Breon, M. Leroy, A. Podaire, A. Bricaud, J.C., Buriez, G. Seze (1994), The POLDER mission: Instrument characteristics and scientific objectives, *IEEE Trans. Geosci. Remote Sens.*, 32:598-615.

Dickinson, R.E. (1983), Land surface processes and climate-surface albedos and energy, *Adv. Geophys.,* 25:305-353.

Holben, B.N. (1986), Characteristics of maximum-value composite images from temporal AVHRR data, *Int. J. Remote Sens.*, 7:1417-1434.

Huete, A.R., C.O. Justice and W.J.D. van Leeuwen (1996), MODIS vegetation index, Algorithm Theoretical Basis Document, http://eospso.gsfc.nasa.gov/atbd/modistables.html.

Kimes, D. S. and Sellers, P. (1985), Inferring hemispherical reflectance of the Earth's surface for global energy budgets from remotely sensed nadir or directional radiance values, *Remote Sens. Environ.*, 18:205-223.

Leroy, M., J.L. Deuze, F.M. Breon, O. Hautecoeur, M. Herman, J.C. Buriez, D. Tanre, S. Bouffies, P. Chazette and J.L. Roujean (1997), Retrieval of atmospheric properties and surface bidirectional reflectances over land from POLDER/ADEOS, *J. Geophys. Res.*, 102(14):17,023-17,037.

Li, X. and A. H. Strahler (1985), Geometric-optical modeling of a conifer forest, *IEEE Trans. Geosci. Remote Sens.*, GE-23:705-721.

Li, Z., J. Cihlar, X. Zheng, L. Moreau and H. Ly (1996), The bidirectional effects of AVHRR measurements over boreal regions, *IEEE Trans. Geosci. Remote Sens.*, 34:1308-1322.

Matthews, E. (1983), Global vegetation and land use: New high resolution data bases for climate studies, *J. Clim. Appl. Meteorol.*, 22:474-487.

Privette, J. L., W. J. Emery and D. S. Schimel (1996), Inversions of a vegetation reflectance model with NOAA-AVHRR data, *Remote Sens. Environ.*, 58:187-200.

Running, S.W., R.B. Myneni, R. Nemani and J. Glassy (1996), MODIS LAI and MODIS FPAR algorithm theoretical basis document, http://eospso.gsfc.nasa.gov/atbd/modistables.html.

Sellers, P.J., S.O. Los, C.J. Tucker, C.O. Justice, D.A. Dazlich, G.J. Collatz and D.A. Randall (1994), A revised surface parameterization (SiB2) for atmospheric GCMs. Part II: The generation of global fields of terrestrial biophysical parameters from satellite data, *J. Climate*, 9:706-737.

Strahler, A.H., M.J. Barnsley, R. d'Entremont, B. Hu, P. Lewis, X. Li, J.-P. Muller, C.B. Schaaf, W. Wanner and B. Zhang (1995), MODIS BRDF/albedo product: Algorithm theoretical basis document, Version 3.2, http://eospso.gsfc.nasa.gov/atbd/modistables.html.

Tucker, C.J. (1996), History of the use of AVHRR data for land applications, in Advances in the Use of NOAA AVHRR Data for Land Applications (G. D'Souza et al., eds.), ECSC, EEC, EAEC, Brussels, pp. 1-19.

Walthall, C.L., Norman, J.M., Welles, J.M., Campbell, G. and Bald, B.L. (1985), Simple equation to approximate the bidirectional reflectance from vegetative canopies and bare soil surfaces. Appl. Optics 24:383-387.

Wanner, W., X. Li and A. H. Strahler (1995), On the derivation of kernels for kernel-driven models of bidirectional reflectance, *J. Geophys. Res.*, 100:21077-21090.

Appendix I. LIST OF ACRONYMS

5S	Simulation of the Satellite Signal in the Solar Spectrum
6S	Second Simulation of the Satellite Signal in the Solar Spectrum
ADEOS	Advanced Earth Observing System
AGRISTARS	Agricultural and Resources Inventory Through Aerospace Remote Sensing
AirMISR	Airborne MISR
AirPOLDER	Airborne POLDER
AM-1	Morning pass EOS platform
APAR	Absorbed Photosynthetically Active Radiation
ASAS	Advanced Solid State Array Spectroradiometer
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
BOREAS	Boreal Ecosystem Atmosphere Study
BRDF	Bidirectional Reflectance Distribution Function
CLAVR	Clouds from AVHRR
DBH	Diameter at Breast Height
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
fAPAR	Fraction of APAR
FASIR	Fourier wave Adjustment, Solar zenith angle adjustment, Interpolation and Reconstruction
FIFE	First ISLSCP Field Experiment
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
ISLSCP	International Satellite Land Surface Climatology Project
LACIE	Large Area Crop Inventory Experiment
LAD	Leaf Angle Distribution
LAI	Leaf Area Index
LBA	Large Scale Biosphere-Atmosphere Experiment in Amazonia
LIDAR	Light Detection and Ranging Instrument
LOWTRAN	Low Resolution Transmittance Model
LUT	Look Up Table
MAS	MODIS Airborne Sensor
METEOSAT	Geosynchronous Meteorological Satellite
MISR	Multiangle Imaging Spectroradiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MODTRAN	Moderate Resolution Transmittance Model
MSG	Meteosat Second Generation satellite
MVA	Multiple View Angle
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
PAR	Photosynthetically Active Radiation
PARABOLA	Portable Apparatus for Rapid Acquisition of Bidirectional Observations of Land and Atmosphere

POLDER	Polarization and Directionality of Earth's Reflectances
SLICER	Scanning Lidar Imager of Canopies by Echo Recovery
SPOT	Satellite pour L'Observation de le Terre
SWIR	Shortwave Infrared
TM	Thematic Mapper
V/H	Vertical to Horizontal Ratio
VI	Vegetation Index

Appendix II. REPORTS FROM THE BREAK-OUT DISCUSSIONS

The first four discussion groups were challenged to define "What have we learned to date, and why is it important" for unique topics (vegetation indices, surface structure and texture, radiometric properties and satellite data correction). The second four discussions, occurring on the second day, addressed future research and applications of BRDF technology. The following reports were prepared by the break-out discussion leaders and rapporteurs, and in some cases were edited by some or all of the respective discussion participants. Although some of the information in these reports may not be endorsed by the entire group, the reports are nevertheless interesting, useful and provocative. Thus, they are presented below unedited save for minor formatting changes.

1) Vegetation Indices (Day 1)

Leader: Louis Steyeart
Rapporteur: K. Fred Huemmrich

A Vegetation Index (VI) is created by combining remotely sensed data from multiple bands to form a single value, with the purpose of enhancing the vegetation signal while suppressing extraneous factors. Over the last 15 years, VIs have been widely used in remote sensing studies for the estimation of biophysical variables such as LAI or fAPAR, mapping of land cover types, and examination of spatial and temporal vegetation dynamics. Extensive use of VIs in such disciplines as remote sensing science, ecology, hydrology, atmospheric modeling, and agricultural monitoring and forecasting led to the discovery and exploration of problems and limitations associated with these measures, resulting in calls from the user community to improve the processing stream and provide standardized products such as the Pathfinder 1, and 8 km AVHRR and International Satellite Land Surface Climatology Project (ISLSCP) Initiative 1.

Variability in VIs arises not only from vegetation dynamics but from factors such as instrument calibration, navigation and geometric registration errors, atmospheric effects, subpixel water and clouds, image compositing, viewing and illumination geometries, and landscape features such as topography. Progress in data processing has been partly driven by user requirements for VIs which are sufficiently stable to permit meaningful comparisons of spatial and temporal variability and change-detection studies. Present studies indicate the need to reliably observe VI variations over 10-day, monthly, and seasonal time periods. BRDF modeling has contributed to this end by improved atmospheric correction, and adjustment of sun and view angle effects by either normalizing data to hemispheric reflectances or correcting to a common sun and view angle alignment, all of which facilitate more appropriate comparison among pixels.

Initial use of VIs relied upon empirical relationships to vegetation characteristics; however, over the years, a better understanding of how the VI data transform works has emerged. Much of this work has involved the Normalized Difference Vegetation Index (NDVI), one of the oldest and most widely used VIs. A strength of the NDVI is that, as a ratio of spectral bands, it effectively reduces noise common to both bands. As the noise in the satellite data is decreased by addressing the factors described above, the need for the noise reduction of ratio indices is reduced. NDVI and other VIs can also be affected by characteristics of the vegetation canopies such as soil background reflectance, leaf angle distributions, canopy structure, and leaf optical properties. Much of this understanding is based on analyses performed using BRDF models. Users prefer a linear relationship between a VI and derived biophysical parameters, which simplifies not only the extraction of meaningful information about a parameter over its entire range of values but also transfer between various spatial scales. It has become clear that different VIs are needed to estimate specific biophysical parameters, and that no single index is appropriate for retrieval of all quantities of interest. For example, for many vegetation types LAI and fAPAR are not linearly related to each other, and consequently no single VI will produce linear relationships with both parameters. Research indicates that to improve retrievals of biophysical variables using VIs, stratification by land cover type should first be performed, due to effects caused by canopy structure variations, leaf optical properties, and background reflectances. Future work will refine the use of VIs, as well as explore VIs based on new data sources such as hyperspectral and multiangle data. Fusions of optical data with thermal and radar data may also generate an entirely new type of VI.

VIs are useful surrogates of multiband remote sensing measurements and are an effective bridge between remote sensing and ecologists. Because of their utility, ease of application, and widespread familiarity, the use of VIs will persist for some time in the future, both in new data collections and in historic analyses.

2) Surface Structure/Texture (Day 1)

Leader: James Irons

Rapporteur: Bobby H. Braswell

The group was charged with discussing what we have learned about surface structure and texture from BRDF investigations and why the acquired knowledge is important. Further, the group was charged with considering a list of issues directed toward improving our ability to exploit BRDF information. A lively discussion ensued with the comments focused principally on vegetation canopy architecture at different scales.

The group agreed that, at the most basic level, BRDF research has led to the widespread recognition of the directional anisotropy of electromagnetic radiation scattered or emitted from terrestrial surfaces. The assumption of a Lambertian surface is, in general, no longer considered acceptable when studying the scattering, emission, disposition, or utilization of the shortwave and longwave radiation driving terrestrial processes. Going one step further, BRDF research has greatly advanced comprehension of the scattering and emission processes, leading to a recognition of the structural properties determining bidirectional reflectance distribution functions (BRDFs) for different types of surfaces, to the formulation of models that predict BRDFs as a function of these structural properties, and to an emerging capacity to retrieve structural parameters using inversion techniques that fit the models to multiangle observations.

The participants recognized that the importance of these advances was tied to spatial scale. At global and continental scales, our understanding of BRDFs is leading to the capability to synoptically map radiative properties such as albedo and fAPAR and to normalize radiances and VIs for variability in solar illumination and view directions. These capabilities will in the near future be realized in products from the EOS AM-1 platform; products that are expected to advance capabilities to identify, characterize, and map ecosystem type and heterogeneity and to monitor global vegetation dynamics. At the scale of a forest stand, the maturation of geometric optical models has led to a capability to retrieve the density, distribution, and relative dimensions of the canopies comprising a stand. A potential connection was noted between this description of stand structure and the operation of preferred pathways for gas and energy fluxes (i.e., gaps) in the stand. At the scale of an individual canopy, both one-dimensional and three-dimensional radiative transfer models have developed, relating internal canopy structure (LAI, Leaf Angle Distribution [LAD], etc.) to BRDFs. At the subpixel scale, we discussed the potential for using multiangle data in concert with spectral data to better decompose or unmix pixels into end-member proportions. At all scales, BRDF models and knowledge provide a more realistic lower boundary for atmospheric radiative transfer models leading to improved capabilities for the atmospheric correction of remote sensing data. Finally, our improved understanding of BRDFs allow us to better design both experiments and remote sensing systems that either exploit or control for the directional anisotropy of scattered and emitted radiation.

Several issues emerged with respect to our ability to more fully exploit our expanded understanding of BRDFs. One issue noted was the limits in the range of applicability of specific models or types of models. No available model relates a generalized parameterization of surface structure to BRDF for all types of ecosystems or land cover. Current applications of BRDF models over large areas require the matching of specific models to different areas by, for example, the a priori mapping of land cover or by the use of models as kernels. Another issue was the linkage between the structural parameters determining BRDFs and those parameters governing ecosystem patterns and processes. We recognized a need to engage ecologists, climatologists, and other Earth system scientists in collaborative research to establish these linkages.

Lastly, the participants looked forward to the near-term collection and distribution of multiangle data from satellite platforms, particularly from POLDER and MISR. The temporal and geographic context of bidirectional measurements from space are expected to provide a basis for a new generation of simple models linking directional surface reflectances to parameters of substantial ecologic and climatologic importance. The temporal and spatial patterns of BRDF descriptors will demonstrate in a highly effective way how to tune the retrieval algorithms as well as validate the simplification of the physics in the new generation of BRDF models. Mapping and monitoring of both the BRDFs and the retrieved surface parameters for large regions will provide exciting new information, validating and extending the utility of multiangle angle observations.

3) Radiometric Properties (Day 1)

Leader: John M. Norman

Rapporteur: Philip Lewis

Since remotely-sensed measures at optical wavelengths are themselves directly related to the radiometric properties of the area being viewed (modulated by the intervening atmosphere), the task of derivation of radiometric properties of the surface should be one of the more straightforward objectives and achievements of terrestrial Earth observation science. The spatial and temporal monitoring of surface radiometric properties is of interest to a variety of communities requiring information on surface shortwave energy budgets, such as climate modelers and weather forecasters, as well as those interested in (ecosystem/agricultural) heat fluxes, water balance and vegetation productivity.

The key parameters of interest are: (i) land surface albedo, which provides the lower boundary condition to surface-atmosphere interactions as well as information on the absorption of surface shortwave fluxes, and (ii) the fraction of absorbed photosynthetically-active radiation (fAPAR), which provides information on the efficiency of Photosynthetically Active Radiation (PAR) absorption by vegetation, and hence the energy available for primary production, etc.

Both of these measures are closely related to, but not defined as, intrinsic surface properties, since their definitions imply a dependency on atmospheric state and solar angles. A spatial and temporal mapping of these variables therefore implies the use of an effective parameterization which produces the correct energy fluxes over the conditions applied by the applications scientist. In the case of albedo, for instance, BRDF modeling studies have shown that it is typically sufficient to provide users with a parameterization of (spectral) directional-hemispherical reflectance (as a function of solar zenith angle) and (spectral) bihemispherical reflectance, which are intrinsic properties. Spectral integration of an "effective albedo" over the entire shortwave region or over separate visible/near infrared wavebands can be achieved, but implies a move away from intrinsic properties towards ones dependent on atmospheric state.

The fundamental description of surface reflectance is the spectral BRDF. Modeling and measurement of surface directional reflectance over recent decades has helped enormously in understanding the factors affecting integrated radiometric properties, to the point where we are now in a position to provide the first generation of operational algorithms for the mapping of such information from space from the forthcoming generation of satellite sensors (POLDER, MISR, MODIS, etc.). This "state-of-the-art" represents a major step forward in providing comprehensive, accurate information of these variables over the first-order approximations that are currently applied. However, the models and methods which are to be applied to data in the POLDER-EOS era do not take the BRDF modeling techniques as far as we in the community believe they can and should be taken in relation to our current understanding of the issues involved, in that they are still reliant on some empirical and semi-empirical models which will not always be applicable.

Both of these radiometric properties can, of course, be mapped using remote sensing data through the surrogate of land cover. Whilst this is of use, such methods do not themselves provide any direct estimates of these variables, as albedo and fAPAR must then be assigned for each cover type.

From the current perspective, we can outline a range of areas in which remote sensing of these parameters has matured over recent decades, and highlight areas in which this has been aided by BRDF research. First, we can note that remote sensing offers the *only* way to obtain comprehensive multitemporal spatial data sets of these variables; without remote sensing, the communities concerned are severely limited in the (spatial and temporal) scale of measurement that can be considered.

Since "albedo" is simply a "brightness" measure, remote sensing scientists have long since attempted to derive estimates of this from the reflectance observed at a single view/illumination angle. BRDF research has shown, however, that the underlying assumption of Lambertian surface reflectance is typically a poor one, leading to errors of typically 10 to 30 percent (Walthall et al., 1985). A key advance in the estimation of (green) fAPAR has come from the realization that there is a fairly good (empirical) linear relationship between this variable and some vegetation indices, notably NDVI. This has been backed up by BRDF measurement campaigns and modeling exercises, and we have, because of this, moved beyond this first basic statement to a realization that the particular empirical relationship varies with the surface cover type, and depends on the vegetation structure and vegetation (and soil?) radiometric properties. There is also extensive evidence from the BRDF community that measures related to VIs can vary strongly with viewing and illumination angles and that such effects are often not well compensated in current compositing techniques. Further, the inversion of BRDF models with remotely-sensed data provides a useful mechanism for a physically-based approach to modeling fAPAR.

The BRDF community has participated strongly in the move from qualitative to quantitative remote sensing, in deriving models based on biophysical characteristics of the surface which affect the reflected radiation field and in furthering the requirements of remote sensing scientists for better quality data of surface reflectance properties. This has involved a recognition in the remote sensing community that improvements in estimates of surface parameters will only be achieved through improvements in: atmospheric correction; accounting for or making use of surface anisotropy; cloud clearing algorithms; sensor calibration; coregistration of multiangle/ multitemporal data; and the selection of appropriate wavelengths/wavebands.

4) Satellite Data Correction (Day 1)

Leader: Eric F. Vermote

Rapporteur: Satya Kalluri

Discussion was aimed at establishing the progress made in the past 15 years in the area of satellite data correction prior to analysis for surface information. Generally, the conclusion is that data sets from the past 15 years have been testbeds for satellite data correction and many problems have been identified and are now amenable to partial correction on new satellite systems such as POLDER (launched 8/96) and EOS (to be launched in 1998). Several topics were discussed, including calibration, atmospheric correction, cloud screening, and geometric correction.

The importance of calibration has been recognized due to the transition of using remote sensing as a qualitative tool to using it as a quantitative tool (i.e., with physically-based approaches). In other words, going from instrument counts to reflectance signals. This problem cannot be overemphasized since vegetation reflectance becomes saturated (ceases to change for a change in the canopy) under some (dense) conditions. The only possible way to reliably quantify vegetation with remote sensing is to accurately measure small variations in the reflected signal. The meteorological satellites employed by the terrestrial remote sensing community have only begun to achieve the required levels of accuracy. Thus, calibration is an essential step before atmospheric correction to obtain accurate surface reflectance. Calibration uncertainty decreased from 15 to 20 percent 15 years ago, to the 5 to 7 percent presently possible on AVHRR or Thematic Mapper (TM). For future sensors, an accuracy of 2 percent (relative to sun) is projected. This 2 percent accuracy will be obtained both through better instrument characteristics and innovative approaches to cross calibration of instruments (by viewing the moon) and accurate and redundant on-board calibration system (MODIS). The accuracy of 2 percent on calibration is probably sufficient for BRDF analysis; however, there are strict requirements for interinstrument calibration when multiple sensors are used together to analyze BRDF (such as MODIS and MISR).

In the area of atmospheric correction, intensive modeling has been done in the past few years with the emphasis on providing simple tools to assess/correct atmospheric effects for the remote sensing community (Low Resolution Transmittance Model [LOWTRAN], Simulation of the Satellite Signal in the Solar Spectrum [5S], Moderate Resolution Transmittance Model [MODTRAN], Second Simulation of the Satellite Signal in the Solar Spectrum [6S]). The development made on processing global data sets has gone from no correction, to correction of rayleigh and ozone effects (AVHRR-Land Pathfinder), to a projected correction of all gaseous absorption effects, aerosols, thin cirrus clouds, radiative coupling between the surface BRDF and atmosphere and adjacency effects for the next generation sensors. Once again, these corrections will be possible on future sensors on an operational basis because of their designs (i.e., multidirection, multispectral or polarization capability, simultaneous acquisition of multiple parameters from different sensors). In contrast, the currently used corrections do not perform sufficient removal of atmospheric effects to reliably and consistently provide reflectances useful for BRDF studies. However, the limitations of the new atmospheric correction schemes in terms of accuracy are not fully taken into account in the presently proposed inversion schemes. The expected accuracy will be better in the longer wavelengths and probably insufficient in the blue band for BRDF inversion. This needs to be addressed in future inversions.

The importance of a cloud screening to select "good" observations was pointed out during the report of the working group. In this area, good progress has been made too, and although the current operational algorithm for AVHRR, (CLAVR) is known to be too conservative (rejects too many pixels), future sensors will be equipped with more spectral bands that will refine the cloud screening to keep more observations.

Because current sensors sample a location only once per satellite pass, accurate registration and geometric correction is essential for BRDF studies (that use pixels obtained at different geometries and at different times). Good progress has been made in orbit prediction and attitude correction techniques that provide ± 1 km accuracy for the AVHRR. For future sensors, the presence of both high spatial resolution and moderate spatial resolution sensors on the same platform and the advances in platform attitude control and determination will enable subpixel registration accuracy.

A discussion took place to assess how remote sensing benefits from recent advances in computers. It is true that computer efficiency has increased greatly during the past 15 years but the objectives and complexity of the science algorithms, and the size of the input data sets, have increased as well. Indeed, as our computational potential has increased, our demands for accurate results have also increased. Also the group noted that there was a large gap between new technology (massively parallel computers, etc.) and what is currently available for operational remote sensing data processing (EOSDIS) that tends to stay on the safe side of technological advances in computers. More liberal access to these new technologies may greatly increase the BRDF community's potential for robust, large-area analysis with physically-based models.

5) How can we exploit current and next generation sensors by applying mature aspects of BRDF understanding? (Day 2)

Leader: Siegfried A. W. Gerstl

Rapporteur: Crystal Barker-Schaaf

The group discussion started with classifying AVHRR, Geostationary Operational Environmental Satellite (GOES), Geosynchronous Meteorological Satellite (METEOSAT), ASAS, Portable Apparatus for Rapid Acquisition of Bidirectional Observations of Land and Atmosphere (PARABOLA) and even Airborne POLDER (AirPOLDER) and MODIS Airborne Sensor (MAS) as current sensors, and the EOS sensors (MODIS, MISR, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), POLDER, Meteostat Second Generation satellite (MSG), and Airborne MISR (AirMISR) as future generation instruments. There was general agreement that use of BRDFs to correct data for directional effects has become routine and has significantly enhanced the potential for identification of vegetation parameters and other land cover characteristics.

The conversation shifted to a spirited discussion on the *mature* aspects of BRDF research as related to the retrieval of vegetation parameters. Modeling efforts have encompassed the macrostructural (landscape and regional scales, mostly heterogeneous) situations as well as the microstructural cases (canopy and leaf scale, mostly homogeneous across a pixel). The difficulty lies in relating the effective (or apparent) parameters which are remotely sensed to the biophysical parameters needed by ecologists and agronomists for their application models. There was a general consensus that there needs to be more progress in the development of models to make this link. Furthermore, additional structural parameters on the canopy scale may be identifiable from a more thorough investigation of the special cases of hotspot and specular BRDF measurements and appropriate 3-D models. Generally there was an observation that there simply have not been sufficient "clean data sets" available to fully test and verify these relationships.

The modelers in the group pointed out that the existing complex models (with full 3-D geometry description) do an excellent job of characterizing surface BRDFs but are still difficult to invert for biophysical and structural parameters. The simpler models, sometimes seen as synonymous with look-up tables (LUTs), are capable of deriving certain surface parameters for certain cases but they require ancillary information to correctly constrain their applicability. It was pointed out that the modeling purist could reasonably claim that you need as many simple models (or LUTs) as you have pixels. The key is understanding how to generalize the specific details of the complex models and recognizing when such a generalization breaks down, leaving you with only "effective parameters." From the ecologist's viewpoint, the crux of the matter is to define a range of "simple models" (or LUTs) that are applicable to a specific biome and then to be able to select the correct model for any given remotely-sensed pixel. One way to obtain such simpler models would be through parameterization of the solutions from the more complex 3-D models.

In discussing *how* to use the mature aspects of complex modeling of BRDF effects, the use of more comprehensive data sets and of new sensor data ("real satellite data") was coupled with a need to focus on improved inversion techniques to derive stable "true" vegetation parameters. A limited set of structural canopy parameters (5 to 10) with significance to biophysical parameters of ecological and agricultural canopies must be identified. Existing computer graphics-based "complex" models may be used to define this limited number of significant structural parameters by performing virtual remote sensing experiments on the computer (also called "numerical experiments"). This process will lead to the convergence of understanding how to relate remotely-sensed BRDF data to biophysical parameters:

effective parameters	to	*true parameters,*
simple models	to	*complex models,*
few structural parameters	to	*many (more) parameters,*
limited information content	to	*enhanced information content,*
restricted application domain	to	*enlarged domain,*
"absurd" solutions	to	*true solutions.*

The group felt that the majority of the above-mentioned 5 to 10 structural parameters are only measurable with multiangle views and with no other (spectral or spatial) remote sensing signatures. Perhaps a canopy architecture sensor (based on active remote sensing?) is needed to aid in this process!

As for the impact of BRDF research on atmospheric and radiation parameters, there is a genuine feeling that fine-scale BRDF-derived albedos from multidirectional measurements (e.g., from MISR and MODIS) represent a major advance in the state-of-the-art and will be embraced by the climate and energy budget communities because of reduced uncertainties. However, there was some discussion that the real need was for BRDFs (not albedos) so that these researchers could correctly generate radiation fluxes within their own models. Finally there has been a general acceptance of the necessity of BRDFs to specify a more accurate boundary condition in any atmospheric correction or atmospheric simulation effort; assumptions of Lambertian surface reflectances are confirmed as incorrect in most cases and are no longer acceptable.

6) What are the aspects of current BRDF understanding that require future basic research and theory development? (Day 2)

Leader: Michel M. Verstraete

Rapporteur: Stephane Jacquemoud

It is clear that a detailed and accurate understanding of the anisotropic spectral reflectance of natural surfaces is essential to the proper interpretation of satellite remote sensing data in the solar spectral domain. At the very least, the influence of this anisotropy, coupled with the highly directional illumination field, must be accounted for to avoid misinterpretations of the variance present in the raw data. The possibility of exploiting this anisotropy to retrieve additional information provides further motivation to pursue research in this direction.

The group discussions may be organized and summarized along the following four points:

1. The development of new or better BRDF models must be justified by the particular applications and accuracy requirements of the end-users. Indeed, although the study of the anisotropic reflectance of terrestrial surfaces may be of interest in its own right and may ultimately lead to an improved characterization of the structure of these environments, the primary benefit of BRDF research for most users will be an increase in the accuracy and reliability of the results derived from the remote sensing data. It is therefore recommended to take steps to improve the dialogue between ecological end-users of remote sensing data and remote sensing researchers, so that the

former group may have a better appreciation for the potential and limitations for space-based Earth observation techniques, and the latter group may better understand the true needs of the end-users.

2. Specific areas have been identified where further research could lead to significant improvements in models and applications:

• Due to the nature of the physical processes involved, the observation of terrestrial surfaces from space in the solar spectral domain will always take place through the atmosphere, which is known to significantly affect the transfer of radiation, both downward on its way to the surface, and upward after its reflection. In fact, the Earth's surface and the atmosphere are radiatively coupled through such processes as multiple scattering, and the correct interpretation of remote sensing data will always have to account for the joint effects of both geophysical media. Although this problem has been recognized for many years, the solutions implemented so far have been mostly limited to so-called "atmospheric corrections," which assume certain surface properties (such as a black or Lambertian surface) to estimate the atmospheric effects. This approach suffers from serious deficiencies and may lead to spurious results. It is therefore recommended that more emphasis be given to studies focusing on the correct treatment of this problem, namely those that address the coupled problem of radiation transfer in both the atmosphere and at the surface simultaneously.

• A second issue identified as crucial for the effective exploitation of BRDF studies is the further development of efficient and reliable inversion procedures. Indeed, the benefits and advantages of exploiting physically-based or parametric BRDF models hinges on our capability to invert such models against remote sensing data. This approach is potentially more effective than the application of purely empirical methods such as vegetation indices, but it suffers from possible drawbacks including a higher level of complexity, a more substantial drain on computer resources, and a potential sensitivity to noise in the data or initial guesses at the solution. The design, implementation and actual use of advanced robust inversion methods will play a crucial role in the popularization of advanced methods of remote sensing data interpretation.

• The third issue identified by the working group as an area in need of further development is the integration of spectral and directional methods of data analysis. These two domains have been largely perceived as independent, when they should be treated jointly. Indeed, it has been shown that the interpretation and exploitation of the directional variability in the data must take place prior to or at the same time as the spectral analysis of these data; otherwise, the results of the spectral analysis remain dependent on the particular geometry of illumination and observation. It is thus recommended that further effort be directed to the effective exploitation of remote sensing data in all its dimensions, and in particular through the combined use of spectral and directional variabilities.

• The working group discussed in some detail the importance of scale in the interpretation of remote sensing data, especially as it relates to the directional aspects. The lack of detailed understanding of leaf anisotropy was underscored, as it is not clear how this may affect the reflectance of the canopy.. The diversity of surfaces and objects within any given pixel creates specific problems at that scale, since each element has its own anisotropic response. The understanding of the anisotropy at the pixel scale in terms of the anisotropies of the constitutive elements remains poor and may impede the usefulness of instruments with instantaneous fields of view large enough to generally contain a variety of objects. At the next scale up, adjacency effects smear the response of individual areas through the contamination of the spectral and directional response of neighboring pixels. This effect takes place because of the presence of the atmosphere, and therefore constitutes a very difficult problem. Nevertheless, it was thought that progress could be achieved through further investigations of the trade-off between smaller pixels with less diversity but higher adjacency effects.

• Topography remains an issue largely ignored by developers of methods for the analysis of remote sensing data. So far, most, if not all, approaches assume a flat horizontal terrain. This may be appropriate for either very small and approximately horizontal pixels, or for very large pixels containing rolling terrain and structures whose vertical height is much smaller than the horizontal scale of the pixel. In most practical cases, however, the effect of orography may be important, especially when the illumination or the observation angles are not from nadir. Since vegetation does not grow perpendicular to the slope but mostly along the local vertical, results obtained with existing models cannot simply be adapted to account for slope and aspect. Further investigations in this direction are dearly needed.

• Finally, the working group felt that further thoughts should be given to the dichotomy between detailed models which better describe the processes of radiation in particular scenes and more generic models which are less specific but more widely applicable. Ultimately, the choice of a particular model depends on the application and accuracy requirements of the user, as noted above, so it will be wise to develop a panoply of tools to address a diversity of needs, keeping in mind the fact that when specific tools are developed, they create a concomitant need for an associated method to identify the conditions under which they will be applicable.

3. In addition to the specific points raised above, the working group wished to emphasize that the effective use of the understanding gained in recent years on the radiation transfer in coupled geophysical media would not take place operationally unless significant progress was made in designing new inversion approaches. In addition to the traditional minimization algorithms currently used, it was felt that new approaches such as look-up tables, neural networks and genetic algorithms should be further investigated to exploit their advantages when dealing with very large amounts of data.

4. Finally, the working group unanimously agreed that the single most important drawback to the further development of BRDF models at this time is the lack of adequate measurements to constrain these models. Concerted efforts should be made to develop and integrate observations from laboratory, field, airborne and space campaigns, with a view to provide data that might be critical for the evaluation of existing models as well as to provide further impetus in their developments. Remote sensing measurements in the principal plane, and especially around the hot spot and specular reflection conditions, would be most important. Similarly, the acquisition of ancillary data on the structure and properties of the targets being observed will be essential for the evaluation of existing and future models.

7) Where is the need for new in situ data or field studies to advance our understanding or to promote new applications? What needs to be measured (i.e. new ancillary data)? (Day 2)

Leader: David L. B. Jupp

Rapporteur: Jean-Philippe Gastellu-Etchegorry

The Breakout Group 3 met to consider the needs for field information to advance progress and exploit future sensors by providing links between the BRDF knowledge we have and the objectives of its end-users. It was considered for the purposes of the discussion that the use of models, especially simple parametric models, for normalization, atmospheric correction and standard products, were well defined and have their own "internal" validations at their scales of application. Hence the primary discussion was on establishment and validation of land cover structural characteristics and their relationship with measured, as well as modeled, BRDF.

Overall, there was a feeling that major advances could be achieved by using the information tools we have more fully, addressing the issue of scale in both BRDF models and in the practical issue of field measurements over a range of scales and (most importantly) ensuring that BRDF validation is carried out hand-in-hand with the field measurements of our customers. The customers most in mind during the discussion were generally ecologists, plant physiologists and land surface climatologists - but this is not exclusive.

The outcomes of the group discussions may be summarized in four basic recommendations:

Recommendation 1. Refine current designs and specify what is "sufficient" structural, radiometric, ecological, flux and climatological data taken in campaigns.

This message was also implicit in the final day discussion which recommended that base standards and methodology in campaigns be established throughout the world for data that intend to contribute to this research area. It was felt we must ensure that campaigns are not spoiled for want of information that may have been easily collected.

The recommendation can be focused into two special areas of activity:

1.1 Site Structural Information

Base ecological information usually includes layering, cover, species, biomass, carbon storage, and canopy functioning in the form of mass and energy fluxes. Vertical and horizontal distribution of biomass is not often recorded in detail other than layering and cover but is regarded as important by many scientists.

Field campaigns which are aimed to address the BRDF/structure/ecology/flux relationships must record 3-D canopy structure in the form of tree height, crown diameter and height, tree stem distribution and crown structure (e.g., clumped into modules or filled uniformly plus within module or crown LAI). DBH (diameter at breast height) is needed for woody biomass or forestry. "Gapiness," which includes establishing clearing sizes as well as crown openness, is becoming an increasingly important parameter.

Such data have been taken in many campaigns in the past. We must ensure, however, that they are complete and "clean" and possibly standardized for future campaigns. It is especially essential for the data to be geocoded. Hence, the use of Global Positioning System (GPS) technology should be increased as well as new land survey technology for tree data. New rapid traverse instruments such as digital hemispherical data in up- and down-pointing modes, or new digital cameras with GPS and Tilt recorded data (Konica), could be considered.

Since site scale is insufficient for the needs of BRDF at MODIS scale, future campaigns should be complemented with airborne data from laser profilers (e.g., Scanning Lidar Imager of Canopies by Echo Recovery [SLICER]), traditional wide angle aerial photography and airborne scanners such as airborne POLDER, ASAS and AirMISR. These also provide radiometric data.

Scale is intimately linked to the needs of these measurements. While the underlying "fractal" nature of land cover is a debate, the need to measure at scales finer than and coarser than the object scale is not. Scaling properties and measures are themselves key elements of land cover structure.

For example, if the base scale is the tree crown then the finer scales of branch, shoot or module (clumps of leaves) and leaf scale influence the result significantly. Again, the way the data scales from crown to clump and on to stand is a characteristic that determines the remote sensing measurement model. Perhaps this implies a "definition" of what we are calling "structure."

1.2 Radiometric & Ecophysiological Measurements

We need to examine options for relating radiation fields and plant physiology so that the problem of relating canopy spectral BRDF to leaf functioning and fluxes can be tackled.

A special effort is needed to ensure that adequate radiometric data be taken in campaigns. The instrumentation exists and can be developed into compact units. The information content in data from instruments like PARABOLA is very high and some learning is still needed to use it all. The adjective "adequate" in this context means being able to link remotely sensed BRDF to the canopy data. In particular, this implies adequate sampling designs (e.g., a moving PARABOLA) to take account of scale and heterogeneity.

Within the canopy, instantaneous and integrated radiation, especially PAR and Absorbed Photosynthetically Active Radiation (APAR) are needed if the link with plant physiology is to be made. These parameters are important for studying canopy mass (H_2O, CO_2) and energy exchanges. For example, canopy photosynthetic activity is related to both instantaneous APAR and to mean-time APAR because the concentration of the foliar photosynthetic enzyme (Rubisco) is linearly related to PAR time-mean value.

Spectral BRDF signatures and physiological characteristics of the understory, with special emphasis on sunfleck space and time structures, CO_2 and H_2O fluxes and time-mean PAR are needed if the step from the remote sensing measurement model to the plant physiology is to be made in the field data. Unless the links are established in the measurements, the models cannot progress.

At the leaf scale, spectral BRDF signatures and physiological characteristics, such as conductance, nitrogen concentration, leaf area, specific leaf area, chlorophyll, CO_2 (assimilation and respiration) and H_2O (transpiration) fluxes of light and shade leaves are also needed. Time variability and spatial variations should be measured.

Particular attention must be paid to the heterogeneity and the requirements this places on the sampling scheme (in particular, the spatial variability of PAR transmission).

Recommendation 2. Establish what is a sufficient description of land cover to establish a BRDF "typology" that provides an ecological key to the cover and is associated with a stable and consistent BRDF form.[1]

There is a need here to involve ecologists to explain the basis for their structural descriptions and how they are measured in the field as well as BRDF-focused remote sensing scientists to examine how radiation measurements can best complement the data as well as to establish the immediately definable model parameters.

At present, BRDF of surfaces seems to involve a vertical to horizontal (V/H) term only accessible via BRDF and to which spectral data are "blind." Such a composite V/H is not dissimilar to "effective LAI" and involves characterizing biomass layers and the effective V/H properties which integrate over inhomogeneous and heterogeneous patches.

Scale issues are not well established for field data collection. Yet there is a need to collect such data to establish the "typology" at least aircraft scale and eventually at environmental satellite data scale. Hence, a related third recommendation is:

Recommendation 3. Address the problems of characterizing cover at the MODIS scale (1 km) including heterogeneity ("gapiness") and structure (vertical and horizontally clumped distributions of wood and leaves and the V/H ratio).

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[1]BRDF form is taken as BRDF normalized to unit spectral albedo.

A solution will involve characterizing canopy roughness and canopy aerodynamic conductance in the presence of gaps within and between crowns and canopy layers. These characteristics are particularly important for flux calculations in climate and ecological studies. They have direct links with standing biomass in most systems. Scientists are now moving to incorporate heterogeneity in flux models and generalize "roughness" - we can be ready to describe and measure canopies in this way. Remote sensing in general and BRDF in particular are currently the only available means to assess this factor over regions or at global scales.

Spatial BRDF signatures should be established using low flying airborne instruments (e.g., PARABOLA, POLDER, ASAS, etc.). Even video and aerial photography data can help establish land cover/BRDF form consistency over the patch sizes needed. The advantage of airborne scanners is that, provided effective collateral data are taken (such as atmospheric aerosol properties), the data are able to be related to reflectance.

It is possible that land cover structure can be assessed at the broader scale using (scanning) laser profiling and also using very high resolution stereo data from new space instruments such as Earlybird. Again, the "fractal" (or spatial scale) properties must be assessed at scales finer and coarser than the object scale. Among the people present in the group it was felt that this scaling was not currently being well handled in field campaigns and is an area where the attention of scientists involved in future missions may need guidance.

Recommendation 4. It is essential that campaigns for site characterization for BRDF be combined with ecological, hydrological and/or climatological campaigns so that the information the BRDF contains may be directly keyed into the products that answer the (potential) user's questions and needs.

This recommendation implies that BRDF field campaigns developed by remote sensing scientists must be linked to ecological data collection with purposes related to the objectives of the users *rather than* the needs for BRDF validation. The BRDF modelers must form bridges with both these groups.

For example, the means to include parameters in two or more layered energy balance models can be advanced by being able to separately include sunlit and shaded fractions of leaves and undercover as well as differential understory and canopy temperatures. Thermal, visible and Shortwave Infrared (SWIR) data from multiangles are a function of these. Taking advantage of such potential opportunities requires careful experimental design.

In the case of existing investments in data, such as FIFE and BOREAS, it is important that we review the completeness of the current information for structural and BRDF studies. As much use and review of such data sets as possible should be made before new campaigns are established, as they form the current "state of science" in this field.

8) What benefit is gained from using off-nadir (single or multiple angles) versus nadir-only viewing? (Day 2)

Leader: Charles Walthall

Rapporteur: Gregory P. Asner

a) What studies show evidences of significant improvements in:

1) classification accuracies,

2) biophysical parameter assessments, and

3) radiometric parameter assessments?

b) Can we quantify the benefit? (List examples)

I. A clarification of terminology and focus of the discussion:

"BRDF research" describes the science/research that investigates the physics and physiology of remote sensing signatures, incorporating and emphasizing the bidirectional domain of information. It is clear that BRDF research also had a significant impact on and further advanced the exploitation of the spatial, spectral and temporal information domains of remotely sensed data.

Multiple View Angle (MVA) data describes the measurement and analysis of reflectance data from a single target or scene at three or more view angles.

The issues associated with the use of a single off-nadir view angle were not discussed. The discussions were assumed to be limited to the use of visible/near infrared spectral bands. Few citations of work were put forth by the group during discussions.

II. Benefits of MVA - How the question was approached.

Coming to an agreement on the benefits of MVA was not an easy process. The discussions raised additional questions among the participants, and thus, the issues remain controversial. The use of MVA has been shown to provide benefits in three different ways: 1) providing unique, additional information not present in nadir-only spectral data, 2) providing better information when analyzed in conjunction with nadir-only spectral data, 3) providing a means of removing unwanted sources of variability due to BRDF effects.

Some of the discussion members felt that "directional reflectance data is available in any remotely-sensed measurement" and that it must therefore be addressed. It can either be treated as a source of noise or as a source of information. However, throwing the information away via removal of BRDF effects is ignoring an entire additional domain of information that adds more degrees of freedom to the data set.

III. Benefits of MVA: Its Unique Information Content

The orthogonality of the information content of Multiple View Angle (MVA) data is clear with respect to one goal of environmental remote sensing. Accurate radiometric parameter assessments for quantities such as albedo for land surfaces and phase function for the atmosphere were unanimously agreed upon as uniquely available from MVA data. The anisotropy of terrestrial surfaces and the Earth's atmosphere is now considered "fact" and formulations employing Lambertian characteristics are viewed as unrealistic. Estimates of hemispherical reflectance from nadir measurements have been shown to result in significant errors when anisotropy is ignored.

These findings are the direct result of BRDF research and these quantities are available only from MVA data.

Conjecture concerning biophysical parameter assessments also indicated a potentially unique benefit of MVA data. Two arguments were presented:

1) MVA data includes sufficiently unique information about the physics of scene radiation that it can be used to select the most appropriate approach for parameter retrieval, and 2) tree shape may be uniquely available from MVA data.

The use of MVA data could help decide which model is most appropriate in a given situation for parameter retrieval. The assumption is that the form of the BRDF sampled by a sensor system would provide an indication as to the physics leading to the signature. Given knowledge of the physics, then the most appropriate model could be applied to retrieve parameters of interest with greater accuracy.

The retrieval of tree shape from MVA data was presented as a strong possibility. This has not been shown to be possible with nadir-spectral approaches.

IV. Benefits of MVA: Improvements to Existing Approaches for Parameter Retrievals Over Nadir-Spectral Approaches

1) Classification Accuracy

Improvement in land cover classification accuracy has been realized with the use of MVA data. Recent work by Leroy (1996/7) has demonstrated that the addition of MVA has pushed classification accuracy beyond the 90 percent threshold. This level of accuracy is rarely available via nadir-spectral approaches without ancillary data. The amount of accuracy improvements over spectral methods is debatable. However, achieving 90 percent or greater is considered significant.

2) Removal of Variability Due to BRDF Effects

The correction of imagery to remove unwanted variability from bidirectional effects has also been demonstrated (Van Leeuwen, 1996/7). This approach considers the BRDF outside of nadir or near-nadir data to be noise that once removed will result in improved nadir-spectral-based parameter retrievals or classifications.

3) Biophysical Parameter Retrievals

Improvements in biophysical parameter retrievals are believed to be possible with an MVA approach. It is believed that this will occur due to the adoption of physically-based approaches (e.g., inverse modeling) to analysis. The use of physically-based approaches for parameter retrieval are believed to be promising such that this will provide tools that can be applied "universally," thus avoiding signature-extension problems of nadir-spectral approaches. Several studies have already demonstrated that MVA data can be used with canopy BRDF model inversions to retrieve key biophysical characteristics (Privette et al. 1994, 1996; Braswell et al. 1996). How much improvement MVA approaches will yield beyond the achievements realized using nadir-only measurements remains to be assessed.

V. Other Perspectives

1) BRDF research is relatively recent in the history of remote sensing. Comparing the history of BRDF research with the history of nadir-spectral remote sensing research reveals some interesting differences. The launch of Landsat in 1972 provided widespread nadir-spectral satellite data to many researchers and fostered a significant effort in the "top-down" approach. Physically-based or "bottom-up" research investigating the physics and physiology contributing to spectral signatures or "scene radiation" via field measurements and modeling were begun simultaneously with the top-down analysis and were accepted as critical to the goal of fully realizing the potentials of remote sensing. The Large Area Crop Inventory Experiment (LACIE) and Agricultural and Resources Inventory Through Aerospace Remote Sensing (AGRISTARS) programs drew heavily on the bottom-up analysis to provide guidance for the top-down analysis.

The "bottom-up" effort of remote sensing research was recognized for its significance in the advancement of remote sensing during the spectral-nadir efforts. Once BRDF was approached as another domain to be investigated on its own merits (whether as noise or information), investigation into the physics and physiology leading to BRDF signatures was considered an integral component of the research program. While this program has been underway for some time, the availability of landscape-level data has been limited to aircraft system data sets. The widespread availability of directional data from satellites has only recently been addressed. A satellite sensor system specifically tailored to acquiring data of interest to the BRDF research community, POLDER has only recently (within the last year) been launched and data sets are not yet widely available.

2) It is too early to realistically assess the benefits of MVA approaches relative to nadir-spectral approaches. Limitations to addressing this question include issues of scale, a lack of widespread landscape-level data sets, the logistically intensive nature of processing directional imagery to the point where questions about the surface can be addressed and the difficulty of georegistering MVA imagery.

3) The number of degrees of freedom available from the spectral domain and the number of degrees of freedom available from the bidirectional domain is debatable. Members of the breakout group offered three for each domain. Two of the degrees of freedom from the bidirectional domain appear to be correlated with two of the degrees of freedom from the spectral domain. It was hypothesized that only one degree of freedom from each domain contains unique information. The discussion did not address the capabilities inherent in hyperspectral data; rather, it focused on the relative merits of broad-band multispectral measurements at nadir and off-nadir. The full workshop discussion on this was "lively" and offered no resolution to the issue.

VI. Summary Conclusions

1) The question of the orthogonality of the bidirectional domain to the spectral domain has not been specifically addressed. It is too early to answer this question. The only benefit that is

documented as being unique to MVA data is the retrieval of surface albedo and atmospheric phase function.

2) Benefits of using MVA over nadir-spectral approaches largely fall under the category of improvements to existing goals: the 90 percent accuracy threshold of classification is crossed with the additional information from the BRDF and the removal of image BRDF effects has been shown to improve the results of nadir-spectral analysis. There is a strong belief/evidence on the part of the community that MVA data approaches will provide more accurate biophysical parameter retrievals. The V/H "structural information content" of MVA data is believed to be of sufficient importance to warrant further research to 1) better define it, and 2) better exploit it.

3) The cost/benefit of using MVA over nadir-spectral approaches needs to be addressed. Given the demonstration of unique information content or improvements to classification accuracies and biophysical parameter retrieval improvements, the additional efforts required for handling, calibrating, atmospherically correcting, georegistering and analyzing MVA data must be weighed against the net information/accuracy results gain.

4) The break-out group and the full workshop were asked the following question: Given the choice of a new system to be built, would you choose a system with 16 spectral bands or one with four spectral bands and four view angles? Given this choice, the breakout group and the full workshop both chose four spectral bands and four view angles.

Appendix III.

Workshop on Multiangular Remote Sensing for Environmental Applications
AGENDA

__Wednesday, January 29__

Workshop Goals and Status of Physically-based Models
(Morning Chair: Deering)

9:00 Welcome (Deering)
9:15 Goals and expectations of workshop (Wickland)
9:30 Key question: **How can we improve our ability to exploit BRDF for environmental applications?** (Deering/Wickland)
10:00 BRDF measurement and modeling: Past progress and future challenges (Asrar)
10:30 Break
10:45 Vegetation indices and their limitations for biophysical parameter retrieval (Huete)
11:15 Surface/air BRDF measurements and dependencies (Deering)
11:45 BRDF model inversions and capabilities (Goel)

12:15 Lunch (catered); poster set-up

(Afternoon Chair: Privette)
1:15 Evolution and capabilities of turbid medium BRDF models (Pinty)
1:45 Evolution and capabilities of geometrical optics BRDF models (Strahler)
2:15 New BRDF capabilities from satellites (Leroy)
2:45 EOS operational algorithms for satellite BRDF inversion (Myneni)
3:15 Break—Group photograph
3:30 Breakout discussions: (rapporteurs compile working group reports)

Question for deliberation:
What have we learned to date, and why is it important (re. "applications")?
- vegetation indices (Steyaert / Huemmrich)
- surface structure/texture (Irons / Braswell)
- radiometric properties (fAPAR, albedo, etc.) (Norman / Lewis)
- satellite data correction (Vermote / Kalluri)

2nd layer of consideration:
- model theory/development issues
- data sampling needs
- atmospheric correction issues
- inversion issues
- hardware/software issues; new technology

4:30 Break; continued poster set-up
5:00 Poster session with cash bar
6:30 Splinter session with discussion leaders and rapporteurs
7:00 Adjourn poster session

Thursday, January 30

Applications of BRDF with Simple Models
(Chair: Wickland)

8:30 Working group reports (rapporteurs)
9:00 Simple models for retrieving broadband albedo (Wanner)
9:30 Simple models for landcover identification (Liang)
10:00 Relating simple model parameters to biophysical parameters (Roujean)
10:30 Break
11:00 Simple models applied to BRDF data correction (Li/Privette)
11:30 Simple models for AVHRR NDVI production (Chen)
12:00 Charge to breakout groups (Wickland)

12:10 Lunch (catered)

1:30 Breakout discussions, continued: (rapporteurs compile working group reports)

1) How can we exploit current and next generation sensors by applying the mature aspects of BRDF understanding? (Gerstl / Barker-Schaaf)
   a) vegetation parameters
   b) atmospheric/radiation properties

2) What are the aspects of current BRDF understanding that require future basic research and theory development? (Verstraete / Jacquemoud)

3) Where is the need for new in situ data or field studies to advance our understanding or to promote new applications? What needs to be measured (i.e., new ancillary data)? (Jupp / Gastellu-Etchegorry)

4) What benefit is gained from using off-nadir (single or multiple angles) versus nadir-only viewing? (Walthall / Asner)

5:00 Adjourn
6:00 Group leader & rapporteur dinner
(Chef's Secret, 5810 Greenbelt Rd.; ph. 301-345-6101)

Friday, January 31

Reports and Recommendations
(Chair: Deering)

9:00 Working group reports (rapporteurs)
10:00 Development of recommendations for future directions: synthesis and consensus (Deering/Privette)
11:30 NASA HQ perspectives and summary (Wickland)
12:00 Assignments (Deering)

12:30 Adjourn

1:30 Meeting of writing groups

(Note: For each break-out discussion listed, the discussion leader is listed first, followed by the rapporteur.)

Appendix IV.

LIST OF PARTICIPANTS

No	First Name	Last Name	Affiliation	Country	Email Address
1	Greg	Asner	University of Colorado	USA	asner@cses.colorado.edu
2	Ghassem	Asrar	NASA HQ	USA	gasrar@hq.nasa.gov
3	Alexander	Berk	Spectral Sciences, Inc.	USA	lex@spectral.com
4	Thomas	Brakke	NASA GSFC	USA	tbrakke@ltpmail.gsfc.nasa.gov
5	Bobby	Braswell	University of New Hampshire	USA	rob.braswell@unh.edu
6	Eric	Brown de Colstoun	University of Maryland	USA	ebrownde@geog.umd.edu
7	Jing	Chen	Canada Centre for Remote Sensing	Canada	jing.chen@ccrs.nrcan.gc.ca
8	Jim	Collatz	NASA GSFC	USA	jcollatz@biome.gsfc.nasa.gov
9	Philip	Dabney	NASA GSFC	USA	Philip.W.Dabney@gsfc.nasa.gov
10	Don	Deering	NASA GSFC	USA	ddeering@ltpmail.gsfc.nasa.gov
11	Tom	Eck	HSTX/NASA GSFC	USA	tom@spamer.gsfc.nasa.gov
12	Bill	Emery	CCAR	USA	emery@frodo.colorado.edu
13	Jean-Philippe	Gastellu-Etchegorry	CESBIO	France	gastellu@cesbio.cnes.fr
14	Sig	Gerstl	Los Alamos National Laboratory	USA	sig@lanl.gov
15	Narendra	Goel	Wayne State University	USA	ngoel@tiger.cs.wayne.edu
16	Huadong	Guo	Institute of Remote Sensing Application	China	guohd@irsa.irsa.ac.cn
17	Garik	Gutman	NOAA/NESDIS	USA	ggutman@nesdis.noaa.gov
18	Miroslav	Honzak	University of Wales Swansea	UK	M.Honzak@swan.ac.uk
19	K. Fred	Huemmrich	Hughes STX	USA	fred@ltpmail.gsfc.nasa.gov
20	Alfredo	Huete	University of Arizona	USA	ahuete@ag.arizona.edu
21	Jim	Irons	NASA GSFC	USA	jim_irons@gsfc.nasa.gov
22	Stephane	Jacquemoud	Universite Paris 7	France	jacquemo@ccr.jussieu.fr
23	David	Jupp	CSIRO Earth Observation Centre	Australia	david.jupp@cossa.csiro.au
24	Satya	Kalluri	University of Maryland	USA	sk71@umail.umd.edu
25	Dan	Kimes	NASA GSFC	USA	dan@pika.gsfc.nasa.gov
26	Juri	Knjazihhin	Boston University	USA	jknjazi@crsa.bu.edu
27	Andres	Kuusk	Tartu Observatory	Estonia	andres@aai.ee
28	Marc	LeRoy	CESBIO	France	marc.leroy@cesbio.cnes.fr
29	Philip	Lewis	University College London	USA	plewis@geog.ucl.ac.uk
30	Zhanqing	Li	Canada Centre for Remote Sensing	Canada	li@crs.emr.ca
31	Xiaowen	Li	Boston University	USA	lix@crsa.bu.edu
32	Shunlin	Liang	University of Maryland	USA	sliang@geog.umd.edu
33	Anne	Lifermann	Centre National d'Etudes Spatiales	France	Anne.Lifermann@cst.cnes.fr
34	Chien-hui	Liu	NASA GSFC	USA	chliu@dratmos.gsfc.nasa.gov
35	Alexander	Marshak	NASA GSFC	USA	marshak@climate.gsfc.nasa.gov
36	John	Martonchik	Jet Propulsion Laboratory	USA	jvm@jord.jpl.nasa.gov
37	Elizabeth	Middleton	NASA GSFC	USA	betsym@ltpmail.gsfc.nasa.gov
38	Jan-Peter	Muller	University College London	UK	jpmuller@ps.ucl.ac.uk
39	Ranga	Myneni	Boston University	USA	rmyneni@crsa.bu.edu
40	John	Norman	University of Wisconsin	USA	norman@calshp.cals.wisc.edu

41	Bernard	Pinty	LaMP	France	pinty@opgc.univ-bpclermont.fr
42	Jeff	Privette	NASA GSFC	USA	jeff.privette@gsfc.nasa.gov
43	Wenhan	Qin	NASA GSFC	USA	wqin@ltpmail.gsfc.nasa.gov
44	Hassan	Quaidrari	University of Maryland	USA	hassan@kratmos.gsfc.nasa.gov
45	Jon	Ranson	NASA GSFC	USA	jon@taiga.gsfc.nasa.gov
46	Jean Louis	Roujean	CNRM	France	roujean@meteo.fr
47	David	Roy	University of Maryland	USA	droy@kratmos.gsfc.nasa.gov
48	Carol	Russell	NASA GSFC	USA	car@gyrfalcon.gsfc.nasa.gov
49	Stefan	Sandmeier	NASA GSFC	USA	ssandmei@pop900.gsfc.nasa.gov
50	Crystal	Schaaf	Boston University	USA	schaaf@crsa.bu.edu
51	Lou	Steyaert	NASA GSFC	USA	steyaert@ltpmail.gsfc.nasa.gov
52	Alan	Strahler	Center for Remote Sensing	USA	alan@bu.edu
53	Richard	Thompson	Wayne State University	USA	afn118687@afn.org
54	Wim	van Leeuwen	University of Arizona	USA	leeuw@ag.arizona.edu
55	Vern	Vanderbilt	NASA Ames Research Center	USA	vvanderbilt@mail.arc.nasa.gov
56	Eric	Vermote	University of Maryland	USA	eric@kratmos.gsfc.nasa.gov
57	Michel	Verstraete	Space Applications Institute	Italy	michel.verstraete@jrc.it
58	Pierre	Villeneuve	Los Alamos National Laboratory	USA	pierre@lanl.gov
59	Elizabeth	Walter-Shea	University of Nebraska-Lincoln	USA	agme012@unlvm.unl.edu
60	Charlie	Walthall	ARS Remote Sensing and Modeling Laboratory	USA	cwalthal@asrr.arsusda.gov
61	Wolfgang	Wanner	Boston University	USA	wanner@crsa.bu.edu
62	Diane	Wickland	NASA HQ	USA	Diane.Wickland@hq.nasa.gov
63	Darrel	Williams	NASA GSFC	USA	Darrel.Williams@gsfc.nasa.gov
64	Robert	Wolfe	Hughes STX	USA	robert.wolfe@gsfc.nasa.gov
65	Xiwu	Zhan	University of Maryland	USA	xzhan@geog.umd.edu
66	Zengyan	Zhang	University of Maryland	USA	zengyan@umiacs.umd.edu

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Jeffrey L. Privette, Donald W. Deering, and Diane E. Wickland

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS (ES)
Biospheric Sciences Branch
Laboratory for Terrestrial Physics
Goddard Space Flight Center
Greenbelt, Maryland 20771

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13. ABSTRACT *(Maximum 200 words)*
The NASA Terrestrial Ecology Program sponsored a workshop on January 29-31, 1997, at the University of Maryland to review the progress and the future directions of multiangular reflectance research. The workshop was intended to determine the progress made in bidirectional reflectance distribution function (BRDF) research, the key areas needing new research emphasis, and the mature aspects of BRDF research that can be exploited immediately to support ecological research. This report summarizes the progress made at the workshop, with particular emphasis on the outstanding research problems remaining and the recommendations for improved ecological applications.

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